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Analysis on the Vertical Coupled Vibration between Bogies and Metro Car Body

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Abstract

With a vertical metro vehicle model including the flexibility of car body, the influences of car body stiffness and the coupled vibration between the metro vehicle flexible car body and bogie bounce mode are researched. Results show that the higher the car body stiffness is, the lower the influences of car body flexibility would be on the ride quality and it is the geometric filtering phenomenon rather than the bogie natural frequency of bounce mode that causes the car body resonant vibration. An example study shows that when the first bending frequency of the fully equipped metro vehicle coincides with that of bogie bounce mode, there will not have the resonant vibration of the flexible car body.

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Keywords: Metro Vehicle; Bogie; Flexible Car body; Coupled Vibration

1. Introduction

The metro car body is the structure of fully welded stainless steel and the bogies are low alloy welded, swing arm position type and unit disc braking non-bolster. When we carry out modal analysis and calculate dynamic performance, it has been found that the car body first-order bending frequency is close to that of bogie bounce, which does not meet the requirement of frequencies difference of 1.4. With the development of 3D design, analysis software, the car body structure has achieved excellent lightweight design on the condition that it meets the requirements of strength and stiffness. At the same time, as there are 5 doors on the side wall of the metro, the car body stiffness sharply decreases and the vertical bending

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frequency is lower. The car body vertical first order bending frequency is 7.8Hz by calculating. This paper will analyze whether it is necessary to carry on the adjustment to meet the frequency difference requirements from the bogie and the car body vertical coupling vibration aspect.

2. Metro vehicle vertical dynamic model with flexible car body

In recent years, many experts use different models^[1~4] to study the coupled vibration of rigid and flexible of car body. In this paper, a vertical dynamic model of metro vehicle with flexible car body^[5] is shown in Fig.1. The displacement of flexible car body vibration is $z(x, t)$, in which x is the coordinate being apart from the most left position in the car body and t is time variable; θ_b is car body pitch displacement, z_{t1} , z_{t2} and θ_{t1} , θ_{t2} are the vertical and pitch displacement of bogie1, 2 respectively; $z_{w1} \sim z_{w4}$ are the vertical track irregularity excitations of the 1st to 4th wheelsets respectively.

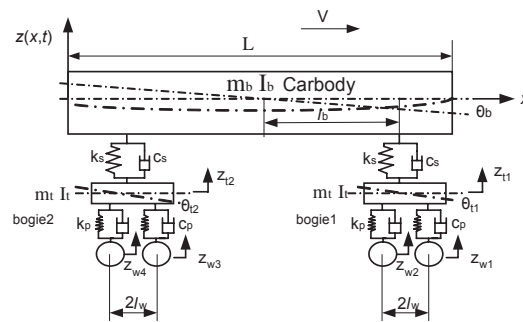


Fig.1 Railway vehicle vertical model with car body flexibility

In order to facilitate the research, this paper supposes the car body being simplified as a uniform Euler-Bernoulli beam and vertical car body vibration displacement being $z(x, t)$, the unit length is ρ , elastic modulus is E , moment of inertia for the section is I , and the damping coefficient is μ . Using the flexible beam vibration theory and considering the car body rigid vibration, the partial differential equation is

$$EI \frac{\partial^4 z(x, t)}{\partial x^4} + \mu I \frac{\partial^5 z(x, t)}{\partial t \partial x^4} + \rho \frac{\partial^2 z(x, t)}{\partial t^2} = P_1 \delta(x - l_1) + P_2 \delta(x - l_2) \quad (1)$$

Where, P_1 is the secondary suspension force of the first bogie (the right side) that imposes on the elastic car body, P_2 is the secondary suspension force of the second bogie (the left side) that imposes on the elastic car body. $\delta(x - l_1)$ is position function of P_1 , $\delta(x - l_2)$ is position function of P_2 .

$$\begin{cases} P_1 = -k_s (z(l_1, t) - z_{t1}) - c_s (\dot{z}(l_1, t) - \dot{z}_{t1}) \\ P_2 = -k_s (z(l_2, t) - z_{t2}) - c_s (\dot{z}(l_2, t) - \dot{z}_{t2}) \end{cases} \quad (2)$$

For the solutions of car body vibration partial differential Equation(1), assuming that i -order mode function is $Y_i(x)$, modal coordinates is $q_i(t)$. When the rigid modes are included with the flexible modes in $z(x, t)$, the first mode of the car body is chosen as bounce of rigid mode and its shape function is taken

as $Y_1(x)=1$. The second mode is pitch and its shape function is $Y_2(x)=L/2-x$ accordingly under the coordinate definition as in Fig.1. When n modes are considered, the vertical displacement of car body can be written as

$$z(x,t) = z_b(t) + \left(\frac{L}{2} - x\right)\theta_b(t) + \sum_{i=3}^n Y_i(x)q_i(t) \quad (3)$$

Here, $z_b(t)$ and $\theta_b(t)$ are modal the coordinate of bounce and pitch modal respectively. The establishment of the model function refers to [6]. When suspended equipment is consolidated under the car body, the functions based on the same principle can be deduced.

Substitute Equation(3) into Equation(1) and perform the integration of the both sides of equation along the car body length, consider the orthogonality of vibration mode functions, one gets

$$m_b \ddot{z}_b(t) = P_1 + P_2 \quad (4)$$

$$I_b \ddot{\theta}_b(t) = P_1 \left(\frac{L}{2} - l_1\right) + P_2 \left(\frac{L}{2} - l_2\right) \quad (5)$$

$$\ddot{q}_i(t) + \frac{\mu l \beta_i^4}{\rho} \dot{q}_i(t) + \frac{EI \beta_i^4}{\rho} q_i(t) = \frac{Y_i(l_1)}{A_i} P_1 + \frac{Y_i(l_2)}{A_i} P_2 \quad i=3, 4, \dots, n \quad (6)$$

Where, $A_i = \rho \int_0^L Y_i(x)Y_i(x)dx$, it can be verified $A_i = m_b$.

3. Influences of car body flexibility on ride quality

To analyze the coupled vibration between bogies and flexible car body, it is assumed that the track irregularity is the American 5 class spectrum (ARR5) [6,7]. The vertical track irregularity time domain spectrum is shown in Fig.2. We can see that the track irregularity power spectral density (PSD) will rise with the increasing of vehicle velocity so as to larger excitation for vehicle. When the velocity is 80km/h, the acceleration PSD comparison between flexible and rigid car body centre is shown in Fig.3 (a). Fig.3(b) shows the acceleration PSD comparison between flexible and rigid car body parts which are above bogies. From the comparison it can be seen that the first-order vertical bending frequency occupies more in the car body centre vibration, at the same time, because of “wheelbase filter” and “bogie centre filter” [8], there is no response at some frequencies.

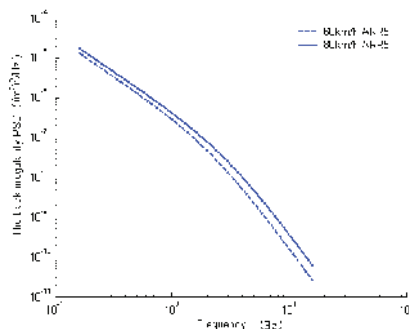


Fig.2 Vertical track irregularity spectrum

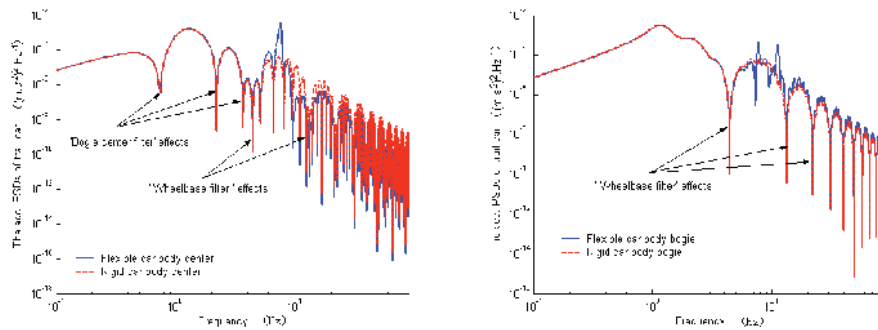


Fig.3 (a) Vertical acc. PSDs of trail car body center; (b) Vertical acc. PSDs above trail car front bogie

The influence of modal frequencies on vehicle ride quality is shown in Fig.4, from which it can be seen that the Sperling index above bogies will increase with the growth of the flexible car body first-order vertical bending frequency. When the car body first-order vertical bending frequency is between 6Hz~7.8Hz, the Sperling index would reach the maximum value. With the increase of car body bending frequency and stiffness, the ride quality will become better if the frequency is over 8Hz. The effect of car body flexibility on ride quality can be ignored on the condition that the bending frequency is more than 12Hz. Through analyzing we can also find there is flexible resonance phenomenon at some frequencies in spite of it is motor car or trail car. The research indicates that, because of “wheelbase filter” effect, when the car body first-order vertical bending frequency is close to $f_3 = nV / (2l_b)$, in which n is integer, V is the running speed, $2l_b$ is bogie centre distance, the car body flexible resonance occurs. From Fig.4 we can see with the car body first-order vertical bending frequency increasing, the flexible resonance phenomenon will be less obvious. That is to say, the higher vertical bending frequency is, the less the flexible vibration and the less influence on ride quality will be.

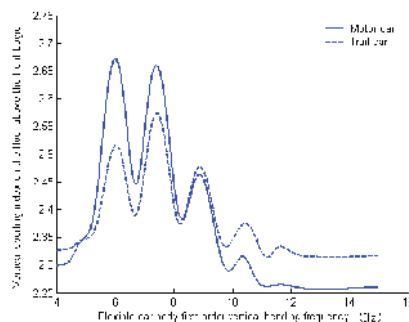


Fig.4 Flexibility influence on ride quality

The ride quality changes of motor car and trail car with velocity are shown in Fig.5(a) and Fig.5(b) respectively. From the figures we can obtain that the ride quality index of car body centre considering car body flexibility is higher than that without considering flexibility. And the higher running speed is, the bigger the influence of flexibility on ride quality will be. However, the Sperling index of flexible car body above bogie is very close to that of rigid one, this is because the point above bogie is nearby the car body first-order vertical bending vibration mode node and the speed is not quite high at the same time, the ride quality index above flexible vehicle bogie is consistent with rigid one.

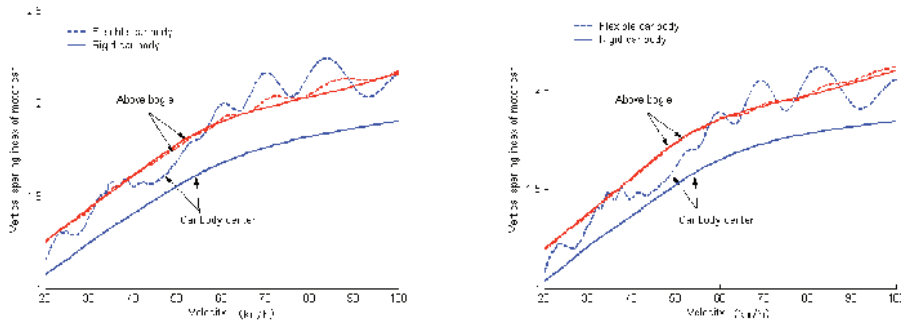


Fig.5 (a) Ride quality changes with velocity of motor car; (b) Ride quality changes with velocity of trail car

4. Coupled vibration between bogies and flexible car body analysis

The analysis above shows the vibration between bogies and car body influences ride quality a lot. The analysis on change of bogie modal parameters with suspension parameters and the research on the change of flexible car body ride quality with bogie bounce mode are needed to be done to decrease this coupled vibration. From the calculation, we can see bogie bounce mode frequency and damping will change a lot when the primary suspension vertical stiffness changes. Bogie bounce frequency increases linearly with the growth of stiffness which shows in Fig.6. That is to say, the bigger the vertical stiffness is, the higher the bogie bounce frequency is. However, the damping ratio is contrary to this above. When the primary suspension vertical stiffness rises from 2MN/m to 4MN/m, if each axle box damping ratio does not change, bogie bounce frequency will decrease to about 30%.

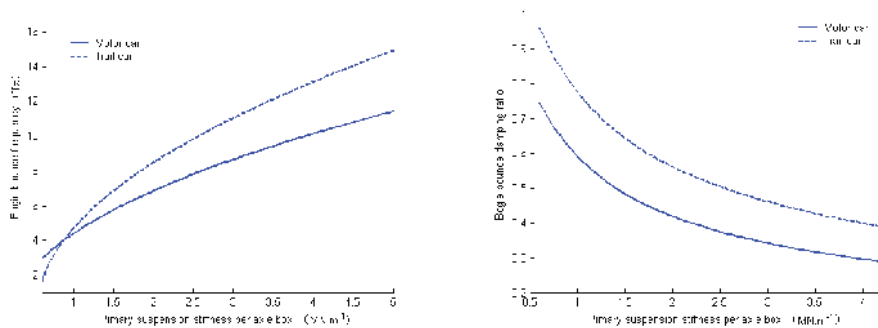


Fig.6 (a) Influences of primary suspension vertical stiffness on bogie bounce frequency; (b) Influences of primary suspension vertical stiffness on bogie bounce damping ratio

Fig.7(a) and Fig.7(b) show the results of bogie bounce frequency influences on the flexible car body ride quality when the running speeds are 60km/h and 80km/h respectively. The results indicate that bogie bounce frequency influences on the flexible car body ride quality will increase obviously with the rise of vehicle velocity; When the vehicle velocity is 80km/h, the trail car ride quality will have a gentle increase with the bogie bounce frequency, while the motor car ride quality will increase more dramatically until it achieves the peak value when bogie bounce frequency is about 8.5Hz where the bogie bounce damping ratio of motor car is much less than that of trail car. The results also show that when the first-order vertical bending frequency of motor car is consistent with that of trail car which achieves 7.8Hz, there is no resonant vibration of the both flexible car bodies. This is the result of the reasonable suspension system parameters and the damping affect jointly.

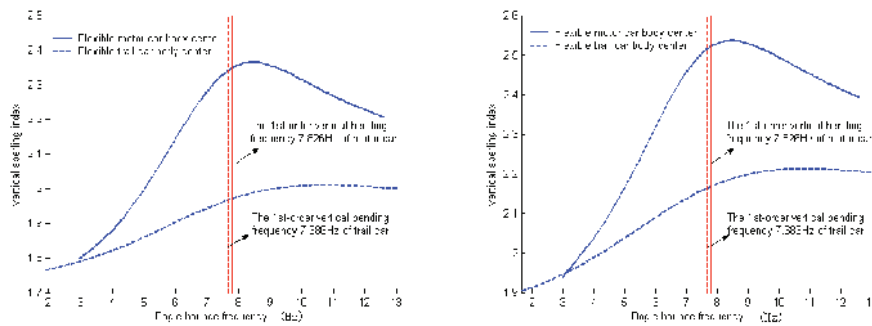


Fig.7 (a) Relations between bogie bounce frequency and vertical ride quality at velocity of 60km/h; (b) Relations between bogie bounce frequency and vertical ride quality at velocity of 80km/h

From the analysis above, we can summarize:

- 1) Influence tendencies of bogie bounce frequency on car body ride quality are basically the same at different velocities;
- 2) Since proper optimal parameters can effectively block the resonance between car body and bogies, we should not pursue the frequency difference value;
- 3) Through calculating, the metro vehicle model in this paper will not have resonance at less than 80km/h in the condition of optimal parameters.

5. Conclusions

A vertical model of metro vehicle which covers car body flexibility and all vertical rigid modes is built, the influences of car body flexibility on ride quality and the coupled vibration between the flexible metro vehicle car body and bogie bounce mode are researched. Results show that the higher the car body stiffness is the lower the influences of car body flexibility would be on the ride quality; For the model studied in this paper, the bogie bounce frequency will increase with the rise of the primary suspense stiffness. Results also show that if the bogie suspense parameters are reasonable, when the first bending frequency of the fully equipped metro vehicle coincides with that of bogie bounce mode, there will not have the resonant vibration of the flexible car body.

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